

ROTOR SIDE CONTROL OF INDUCTION MOTOR

Introduction about Rotor side speed control:

The speed control of induction motor on stator side was explained in previous section. The induction motors are widely used in industrial applications. The stator side control is applicable to both squirrel cage and slip ring induction motors. Because of more advantages, squirrel cage motor is always preferred. In this chapter we shall discuss the speed control of slip ring induction motor i.e., rotor side control.

The slip ring induction motor has a number of disadvantages compared to squirrel-cage motor such as,

- i) wound - rotor machine, is heavier
- ii) Higher cost
- iii) Higher rotor inertia
- iv) Higher speed limitation
- v) Maintenance and reliability problems due to brushes.

The main applications of slip power recovery drives are,

- i) variable speed wind energy systems.
- ii) Large - capacity wind energy systems.
- iii) shipboard VSCF (variable - speed/constant - frequency) systems.
- iv) utility system flywheel storage systems.
- v) variable - speed hydropumps /generators.

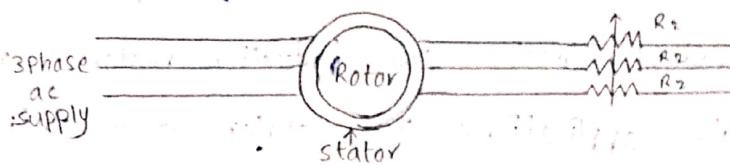
Types :-

- Types of rotor resistance controls are :
- i) conventional rotor resistance control
 - ii) static rotor resistance control
 - iii) slip power recovery scheme.

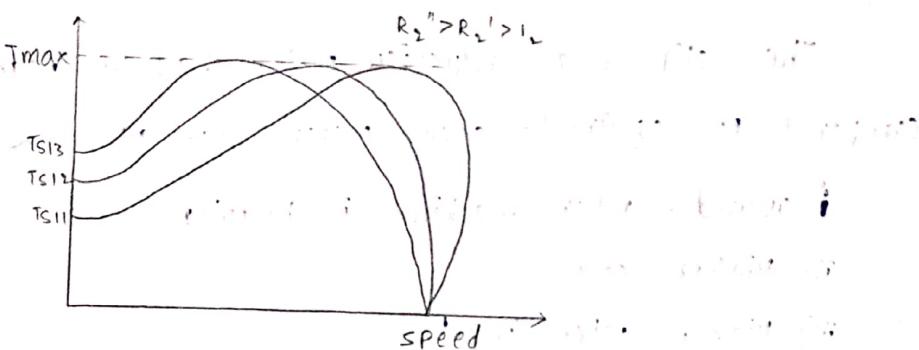
Conventional Rotor Resistance control:

A simple and primitive method of speed control of a slipping induction motor is by mechanical variation of rotor circuit resistance, as shown in figure 8.1

Conventional Rotor resistance control:



This method is only applicable for 'slipping' or 'wound-rotor' induction motor. Here, 3phase ac supply is fed to the stator and a variable resistance R_2 is connected in the rotor side. Here r_2 is rotor resistance.



By varying the rotor circuit resistance R_2 , the starting torque and starting current can be controlled.

The main drawbacks of this method of speed control are:

- i) Reduced efficiency because the slip energy is wasted in the rotor circuit resistance.
- ii) speed changes very widely with load variation
- iii) unbalanced in voltage and current if rotor circuit resistance are not equal.

However, several advantages of this method are:

- i) Absence of in-rush starting current
- ii) Availability of full-rated torque at starting
- iii) High line power factor
- iv) Absence of line current harmonics
- v) smooth and wide range of speed control.

slip-ring induction motor speed control with rotor circuit chopper or static rotor resistance control :-

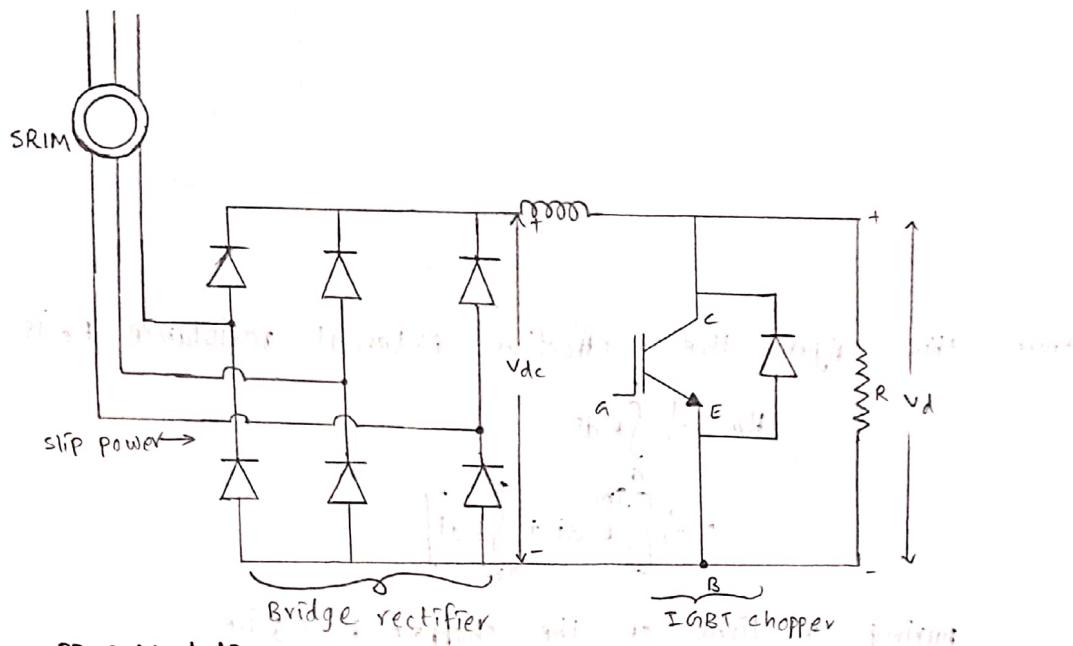
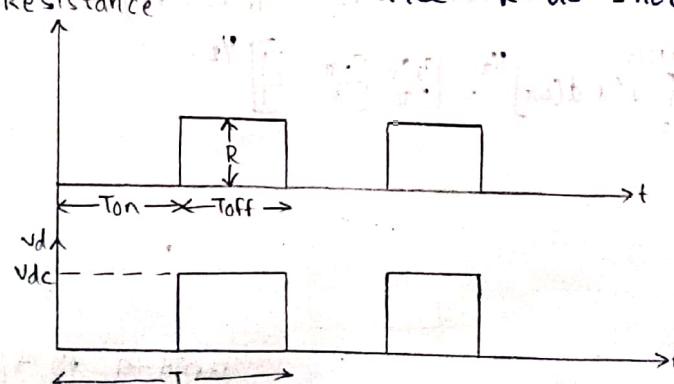


Fig 8.4 :- static rotor resistance control.

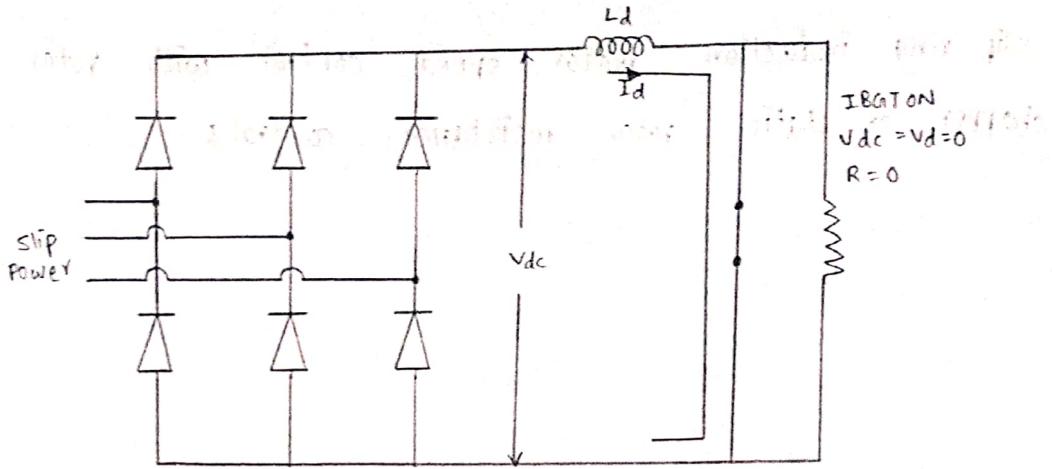
This method of speed control is very inefficient because the slip energy is wasted in rotor circuit resistance. However, advantages are that high starting torque is available at low starting current and improved power factor is possible with wide range of speed control.

The stator of the machine is directly connected to the line power supply and in the rotor circuit, slip voltage is available across the slip rings. This slip voltage is rectified by the three phase diode bridge rectifier.

The DC voltage is converted to current source I_d , by connecting a large series inductor Id . It is then fed to shunt chopper with resistance R as shown figure 8.4.



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From this figure, the effective external resistance R_e is

$$R_e = \frac{1}{T} \int R dt$$

$$= \frac{1}{T} \left[\int_0^{T_m} R dt + \int_{T_m}^T R dt \right]$$

during on time of the chopper $R = 0$; i.e.

$$R_e = \frac{1}{T} \int R dt$$

$$\text{on-time resistance } R_{on} = \frac{R}{T} (T - T_{off})$$

$$\text{off-time resistance } R_{off} = R \left(\frac{T_{off}}{T} \right)$$

The effective resistance between terminals A and B is given by

$$R_e = R(1-\alpha)$$

where $\alpha = \frac{T_{on}}{T}$ = duty cycle of the chopper

T_{on} = on-time of the chopper

T_{off} = off-time of the chopper

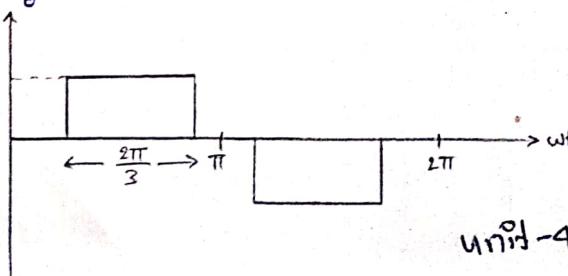
T = Total time of the chopper

Power consumed by effective resistance R_e is

$$P_{AB} = I_d^2 R_e = I_d^2 R(1-\alpha)$$

The rotor current waveform is shown figure. When the ripple is neglected.

$$I_d = \left[\frac{1}{\pi} \int_0^{2\pi/3} I_d^2 d(\omega t) \right]^{1/2} = \left[\frac{I_d^2}{\pi} \left[\frac{2\pi}{3} - 0 \right] \right]^{1/2}$$



$$= \left[\frac{I^2 d}{\pi} \cdot \frac{2\pi}{3} \right]^{1/2}$$

$$I_2 = I_d \sqrt{\frac{2}{3}} \rightarrow ②$$

$$I_d = \sqrt{\frac{3}{2}} I_2$$

Now, the total resistance across the diode bridge is $R_e' = R_d + R_e$
 R_d is the resistance of the inductor I_d

$$= R_d + (1-\alpha)R \rightarrow ③$$

The per phase power consumed by resistance R_e' :

$$P_e = \frac{1}{3} I_d^2 [R_d + (1-\alpha)R] \rightarrow ④$$

Substituting, the value of I_d in eq ④, we get

$$\begin{aligned} P_e &= \frac{1}{3} \cdot \frac{3}{2} I_2^2 [R_d + (1-\alpha)R] \\ &= \frac{1}{2} [R_d + (1-\alpha)R] I_2^2 \end{aligned}$$

This is equivalent to the power dissipation in a resistance of
 $\frac{1}{2} [R_d + (1-\alpha)R]$

caused by the rms rotor current I_2 . Hence, the effective value of resistance per phase is given by

$$R_e' = 0.5 [R_d + (1-\alpha)R] \rightarrow ⑤$$

Slip power recovery system:

This system is mainly used for speed control of slip ring induction motor. The speed of slip ring IM can be controlled either by varying the stator voltage or by controlling the power flow in the rotor circuit.

It has been discussed earlier that the power delivered to the rotor across the air gap (P_{ag}) is equal to the mechanical power (P_m) delivered to the total load and the rotor copper loss (P_{cu}). Thus

$$\text{Rotor Power} = \text{Mechanical Power} + \text{Rotor copper loss}$$

Types of slip power Recovery system:

The slip power recovery system can be classified two types.

i) Kramer system

ii) Scherbius system

These two systems can further be classified two methods.

i) conventional method

ii) static method.

Kramer system:

The Kramer system is only applicable for sub-synchronous speed operation.

The classification of Kramer system is

a) conventional Kramer system

b) static Kramer system.

conventional Kramer system;

The slip ring induction motor is coupled to the shaft of the dc motor. The slip rings are connected to the rotary converter. The dc output of rotary converter is used to drive a dc motor. The rotary converter and dc motor are excited from the dc bus bars or from an exciter. The speed of slip ring induction motor is adjusted by adjusting the speed of dc motor with the help of field regulator.

This system is also called the electromechanical cascade, because the slip frequency power is returned as mechanical power to the slip ring induction motor shaft by the motor.

If the mechanical losses in cascade system are neglected, the shaft power output of the SRIM motor is

$$P_m = (1-s) P_{in}$$

where P_{in} = Input power to the stator

Advantages :-

- 1) The main advantages of this method is that any speed, within the working range can be obtained.
- 2) If the rotary converter is over excited, it will take a leading current which compensates for the lagging current drawn by SRIM and hence improves the power factor of the system.

static kramer system :-

In rotor resistance control method, the slip power is wasted in the rotor circuit resistance. Instead of wasting the slip power in the rotor circuit, resistance, it can be converted to 50Hz ac and pumped back to the line. Here, the slip power can flow only in one direction. This method of drive is called static kramer drive. It is shown in figure. The static kramer drive offers speed control only for sub synchronous speed i.e speed can be controlled less than the synchronous speed is possible.

In this method, the slip power is taken from the rotor and it is rectified to dc voltage 3-diode bridge rectifier. Inductor L_d smoothness the ripples in the rectified voltage V_d . This dc power is converted into ac power by using line-commutated inverter. The rectifier and inverter are both line-commutated by alternating emf's appearing at the slip rings and supply bus respectively. Here, the slip power

flows from rotor circuit to supply, this method is also called as constant torque drive.

Mathematical Analysis :-

Rotor voltage per phase = SE_2

Assuming commutation overlap is negligible, the d.c output voltage of the controlled three phase bridge rectifier is

$$V_d = \frac{3 \times \text{maximum value of input line voltage}}{\pi}$$

∴ $V_d = \frac{3\sqrt{2}(\sqrt{3}SE_2)}{\pi}$ As $[V_m = \sqrt{2}V_L(m.s) \text{ and } V_L(m.s) = \sqrt{3}V_{ph}(m.s)]$

$$= \frac{3\sqrt{2}(\sqrt{3}SE_2)}{\pi} = \frac{3\sqrt{6}}{\pi} SE_2$$

$$\text{But } \frac{E_2}{N_2'} = \frac{V_1}{N_1'}$$

$$E_2 = bV_1, \frac{N_2'}{N_1'} = bV_1, \text{ assuming rotor turns per phase } N_2'$$

where $b = \frac{\text{effective rotor turns per phase } N_2'}{\text{effective stator turns per phase } N_1'}$

$V_1 = \text{supply voltage per phase}$

$$V_d = \frac{3\sqrt{6}}{\pi} sbV_1$$

$$V_d = 2.339 sbV_1 \rightarrow (1)$$

Average dc output voltage for three phase line-commutated inverter is

$$V_{dc} = -\frac{3\sqrt{6}}{\pi} V_1 \cos \alpha$$

$$V_{dc} = -2.339 V_1 \cos \alpha \quad (90^\circ \leq \alpha \leq 180^\circ) \rightarrow (2)$$

Thus,

$$2.339 sbV_1 = -2.339 V_1 \cos \alpha$$

$$\text{or } s = -\frac{1}{b} \cos \alpha \rightarrow (3)$$

Let the transformer turns - ratio be b_T where

$$b_T = \frac{\text{Per phase input voltage to inverter } v_2}{\text{Per phase supply voltage } v_1}$$

Ac output voltage across inverter terminals, $v_2 = b_T v_1$. The inverter dc voltage v_{dc} from equation (22) is given by

$$v_{dc} = -\frac{3\sqrt{6}}{\pi} v_2 \cos \alpha$$

$$v_{dc} = -\frac{3\sqrt{6}}{\pi} b_T v_1 \cos \alpha$$

$$= -2.339 b_T v_1 \cos \alpha \rightarrow (24)$$

with the use of transformer, from eq.(21) and (24), we get

$$2.339 s b v_1 = -2.339 b_T v_1 \cos \alpha$$

$$\text{slip } s = -\frac{b_T}{b} \cos \alpha \rightarrow (25)$$

The resistance of rotor circuit and inductor L_d are neglected,

$$\text{Total slip power, } 3sP_{ag} = v_{dc} I_d$$

$$3s \omega_s T_e = v_{dc} I_d$$

where T_e is the torque developed /phase

$$T_e = \frac{v_{dc} I_d}{3s \omega_s} \rightarrow (26)$$

substituting in equation (21) the values of s from equation (25) and v_{dc} from equation (24), we get

$$T_e = \frac{2.339 v_1 \cos \alpha \cdot I_d}{3 \cdot \frac{b}{b} \cos \alpha \cdot \omega_s}$$

$$T_e = \frac{2.339}{3} \cdot \frac{b v_1 I_d}{\omega_s} \rightarrow (27)$$

when a transformer is used as in fig 8.14, then substitute in eq (27) the values of s from equation (25) and v_{dc} from equation (24) and we get

$$T_e = \frac{2.339 b T}{3} \frac{v_i \cos \alpha \cdot I_d}{w_s}$$

$$T_e = \frac{2.339}{3} \frac{b v_i I_d}{w_s} \rightarrow (28)$$

- i) proportional to dc link current I_d ($T_e \propto I_d$)
- ii) proportional to stator supply voltage v_i ($T_e \propto v_i$)
- iii) proportional to effective rotor to stator turn ratio b , i.e. ($T_e \propto b$)
- iv) inversely proportional to synchronous speed w_s , $T_e \propto \frac{1}{w_s}$

The dc link current I_d is given by

$$I_d = \frac{V_d - V_{dc}}{R_d}$$

R_d = resistance of dc link inductor

$$\therefore \text{slip} = \frac{V_{dc} + I_d \cdot R_d}{2.339 b v_i}$$

$$= \frac{-2.339 b T \cdot v_i \cos \alpha}{2.339 b v_i} + \frac{I_d \cdot R_d}{2.339 b v_i}$$

$$= -\frac{b T}{b} \cos \alpha + \frac{I_d \cdot R_d}{2.339 b v_i}$$

Motor speed w_m is given by

$$w_m = w_s (1 - s)$$

$$= w_s \left[1 + \frac{b T}{b} \cos \alpha - \frac{I_d \cdot R_d}{2.339 b v_i} \right] \rightarrow (29)$$

under steady state condition, from eq (28), total torque $3T_e$, is given by

$$3T_e = T_L = 2.339 \frac{b v_i I_d}{w_s}$$

$$I_d = \frac{w_s T_L}{2.339 b v_i}$$

substituting this value of I_d in eq(29), we get,

$$W_m = W_s \left[1 + \frac{bT}{b} \cos \alpha - \frac{W_s R_d}{(2.339 b v_i)^2} K_T L \right] \xrightarrow{\text{cancel } b \text{ terms}} \text{Eqn 31}$$

and is nothing but the speed with no load on it.

$$\text{Eqn 31} \Rightarrow W_s \left[1 + \frac{bT}{b} \cos \alpha - K_T L \right] \text{ remains same}$$

$$\text{where } K^2 = \frac{m_w \cdot R_d}{(2.339 b v_i)^2} \xrightarrow{\text{cancel } b \text{ terms}} \text{Eqn 32}$$

therefore no load speed will be

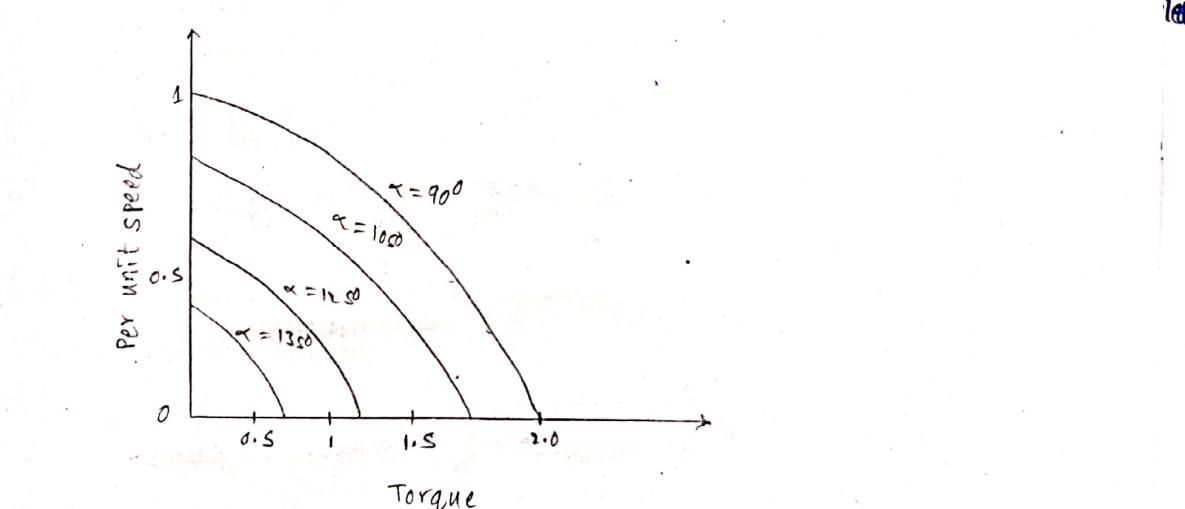
from equation (29) or (31). The no-load speed of the drive is given by

$$\text{Eqn 32} \Rightarrow W_s \left[1 + \frac{bT}{b} \cos \alpha \right] \xrightarrow{\text{Eqn 33}} \text{Eqn 33}$$

which is equivalent to

Figure 8.15 shows the speed torque characteristics of static Kramer drive for open loop system for different firing angles.

These characteristics similar to a separately excited dc motor with armature voltage control.



Now you can see all the firing angles correspond to

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so the torque is maximum at α = 90° and minimum at α = 130°

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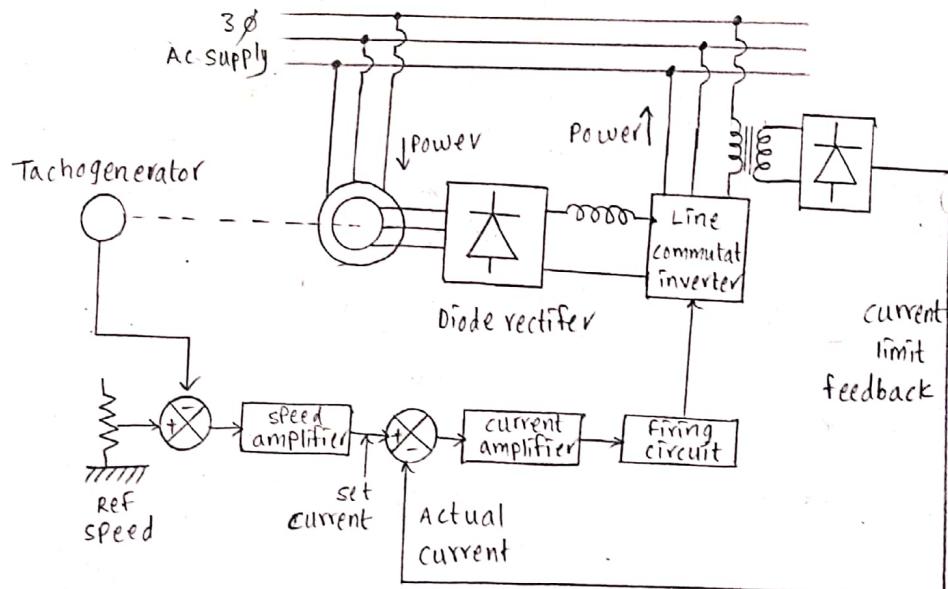
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closed loop control for static kramer system :-

A block diagram of the closed loop control of the SRIM using static kramer system is shown in figure 5.16

The actual speed is fed back from a tachogenerator which is coupled to the SRIM. This actual speed is compared with a reference voltage (ref. speed). The error voltage is amplified by the speed amplifier and set the desired current reference. The current of feedback loop adjusts the current of the system by controlling the firing angles of inverter. This current determines the motor torque. The error voltage is amplified by the current amplifier and fed to the firing angle control circuit of the inverter. Thus, in this system, speed error produces a motor torque which again reduces the error.



The maximum current limit can be set to any desired value by setting the current reference through the speed-error amplifier. Thus the current can be limited to any desired value even under the stalled condition. The acceleration and deceleration is fairly smooth. The cascade drive control system is much simpler and stable than any other variable-speed

slip-ring induction motor drive system in which the rotor slip is measured and controlled.

The scherbius system:

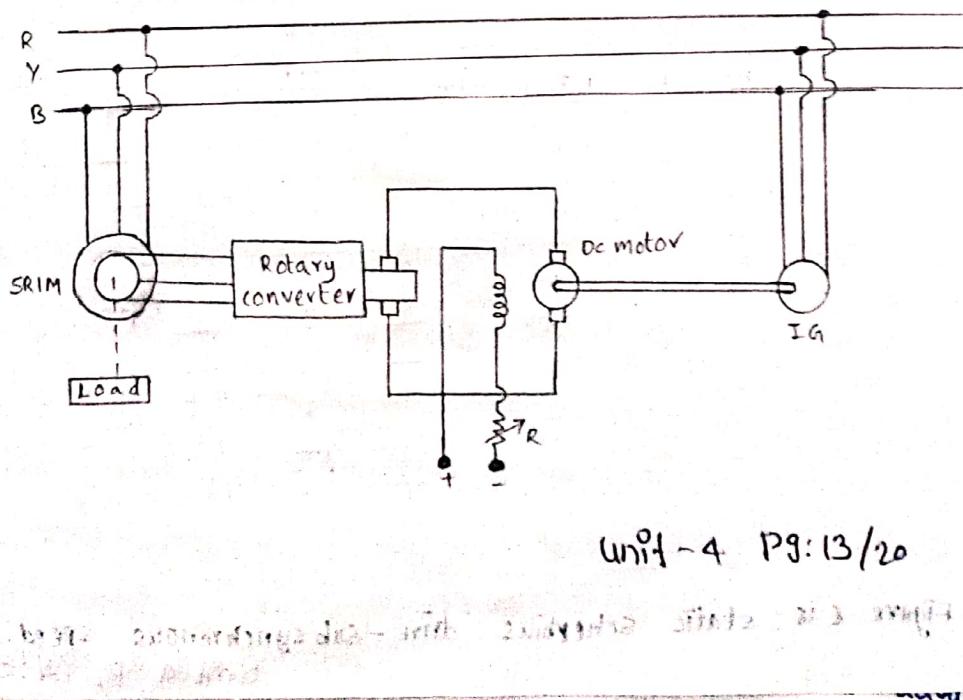
The scherbius system is similar to kramer system but only the difference is that in the kramer system the feedback is mechanical and in the scherbius system the power is electrical. The different types of scherbius systems are

a) conventional scherbius drive

b) static scherbius drive

conventional scherbius drive:

Figure 9.17 shows conventional method of scherbius drive. This method consists of SRIM, rotary converter, dc motor and induction generator. Here, the rotary converter converts slip power into dc power and the dc power fed to dc motor. The dc motor is coupled with induction generator. The induction generator converts the mechanical power into electrical power and returns it to the supply line. The SRIM speed can be controlled by varying the field, regulator of the dc motor.



static scherbius system

For the speed control of SRIM both below and the above synchronous speed, static scherbius drive system is used. This system can again be classified as

1) dc link static scherbius drive

2) cycloconverter static scherbius drive

dc link static scherbius drive:

This system consists of SRIM, 2 No. of phase controlled bridges, smoothing inductor and step up transformer. This system is used for both sub-synchronous speed and super-synchronous speed operation. It is shown in the figure 8.18

i) sub-synchronous speed operation:

In sub-synchronous speed control of SRIM, slip power is removed from the rotor circuit and is pumped back into the ac supply. Figure 8.18 shows the dc link static scherbius system.

The slip power flows from rotor circuit to bridge 1, bridge 2, transformer and returned to the supply i.e.

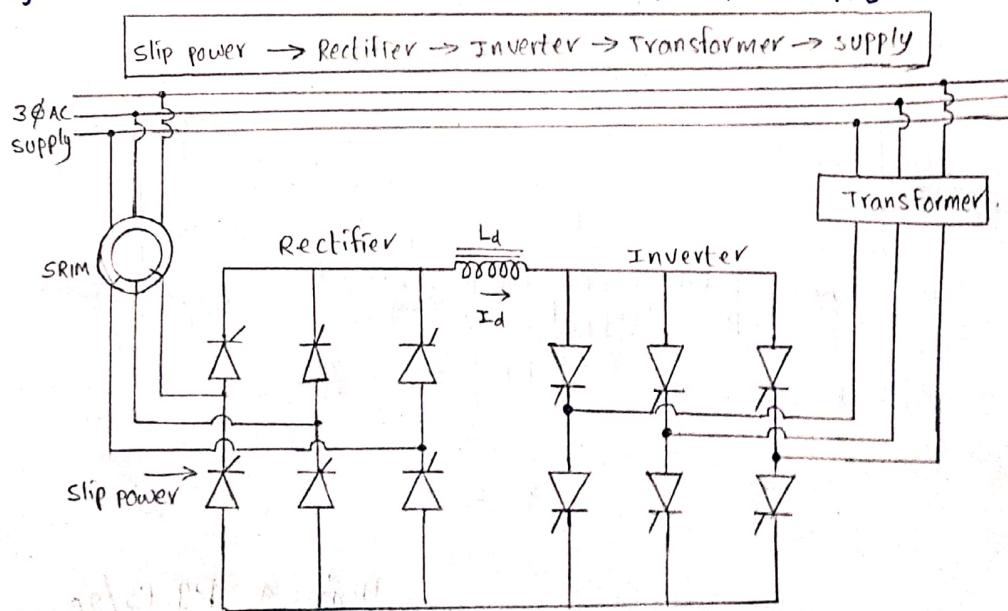
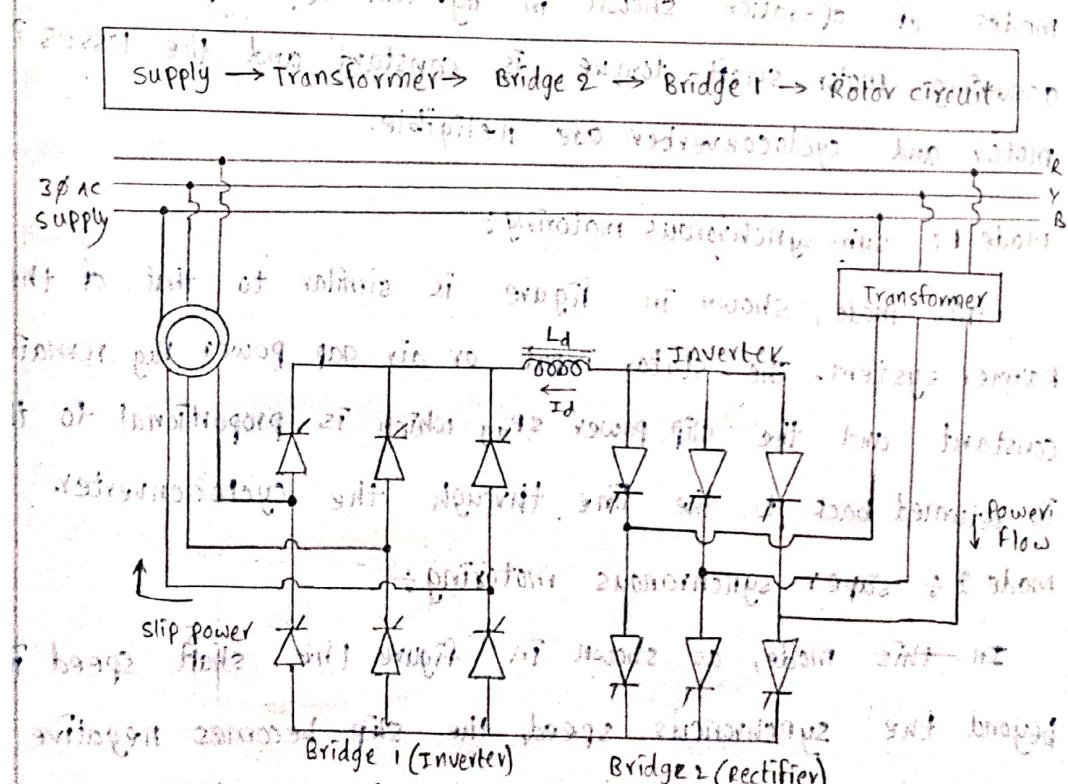


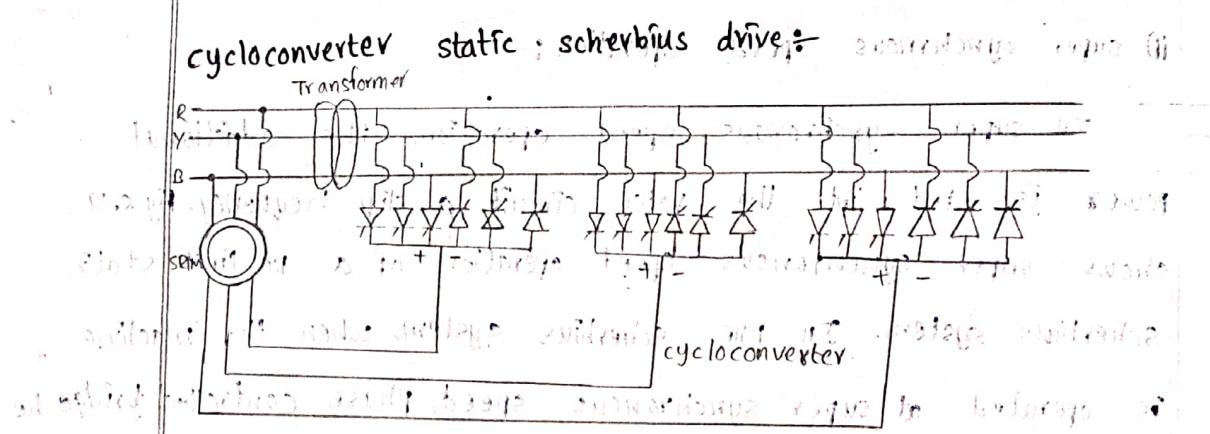
Figure 8.18: static scherbius drive - sub synchronous speed operation
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ii) super synchronous speed operation:

In super synchronous speed operation, the additional power is fed into the rotor circuit at slip frequency. Fig 8.19 shows super synchronous speed operation of a DC link static Scherbius system. In the Scherbius system, when the machine is operated at super synchronous speed, bridge 2 should operate in rectifier mode and bridge 1 in inverter mode. In other words, the bridge 2 has firing angle less than 90° whereas bridge 1 has firing angle more than 90° . The slip power flows from the supply to transformer, bridge 2, bridge 1 and to the rotor circuit.



Near synchronous speed, the rotor voltage is low, and forced commutation must be employed in the inverter, which makes the scheme less attractive. Their replacement of six diodes by six thyristors increases the converter cost and also necessitates the introduction of slip frequency gating circuit. Thus, the provision of super synchronous speed control unduly complicates the static converter cascade system and nullifies the advantages.



The Kármán drive system has only a forward motoring mode of operation. A typical dual-bridge system is shown in fig. 8.20. The dual-bridge converter system in fig. 8.20 can be replaced by a three-phase controlled line commutated cycloconverter, as shown. Here the slip power flow in either direction. The various modes of operation shown in fig. can be explained as follows assuring motor shaft torque is constant and the losses in the motor and cycloconverter are negligible.

Mode 1: sub-synchronous motoring:

This mode, shown in figure is similar to that of the static Kármán system. The stator input or air gap power P_{ag} remains constant and the slip power sP_{ag} which is proportional to the slip, is returned back to the line through the cycloconverter.

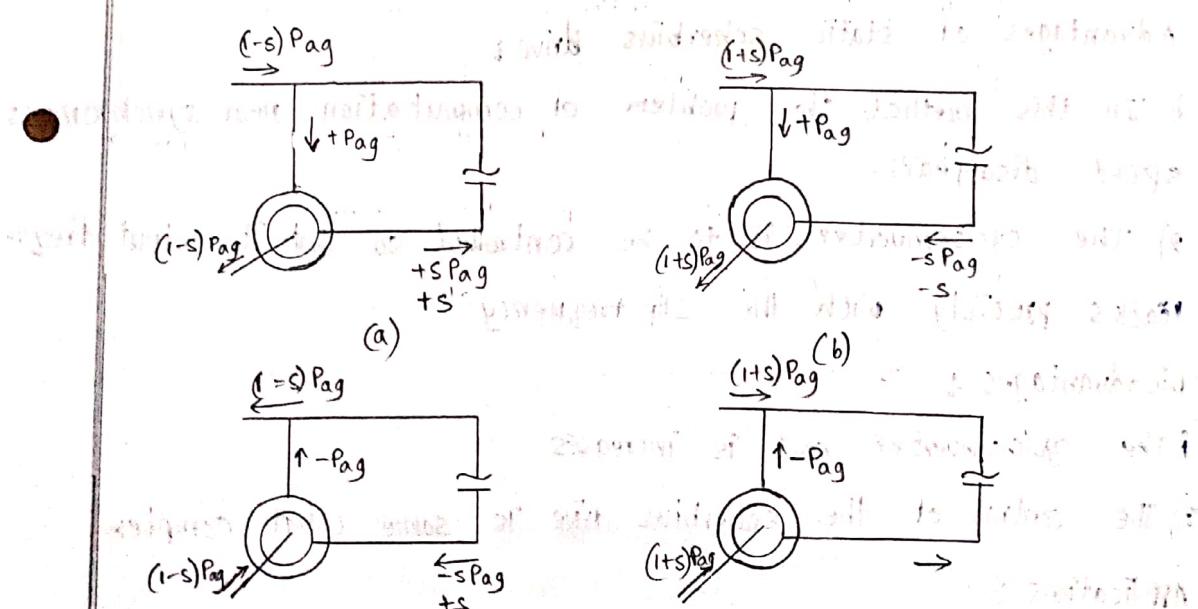
Mode 2: super-synchronous motoring:

In this mode, as shown in figure the shaft speed increases beyond the synchronous speed, the slip becomes negative and the slip power is absorbed by the rotor. The slip power sP_{ag} supplements the air gap power P_{ag} , for the total mechanical power output $(1+s)P_{ag}$. The line therefore supplies slip power in addition to stator input power. During this condition, the slip voltage is reversed, so that the slip frequency-induced rotating magnetic field has opposite to that of the stator.

Mode 3: sub synchronous Regeneration

In regenerative braking condition, as shown in fig 8.21, the shaft is driven by the load and the mechanical energy is converted into electrical energy. With constant negative shaft torque, the mechanical power input to the shaft $P_m = (1-s)P_{ag}$ increases with speed and this equals the electrical power fed to the line. In the subsynchronous speed range, the slip s is positive and the air gap power P_{ag} is negative. The slip power sP_{ag} is fed to the rotor from the cycloconverter so that the total air gap power is constant. The slip voltage has a positive phase sequence. At synchronous speed, the cycloconverter supplies dc excitation current at the rotor circuit and the machine behaves as a synchronous generator. The main application in this is a variable-speed wind generation system.

Mode 4: super-synchronous regeneration



Power distribution as a function of slip in subsynchronous and supersynchronous speed ranged is summarized for all four modes in fig, where the operating speed range of ± 50 percent about the synchronous speed is indicated.

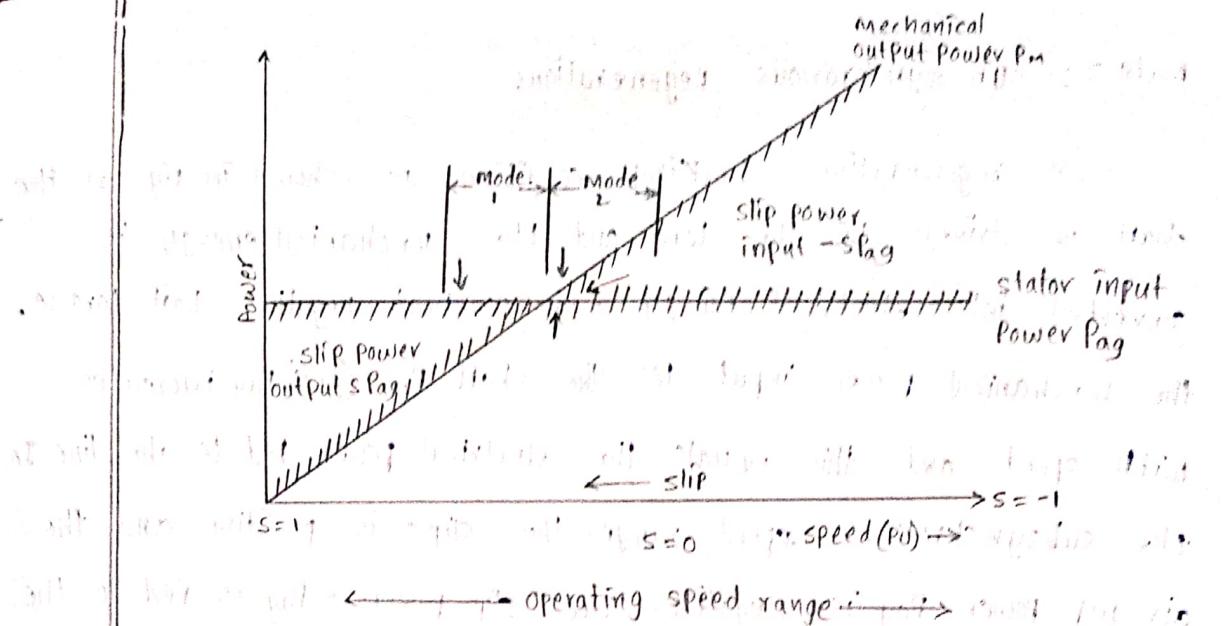


Figure 3.44(a): mode of operation.

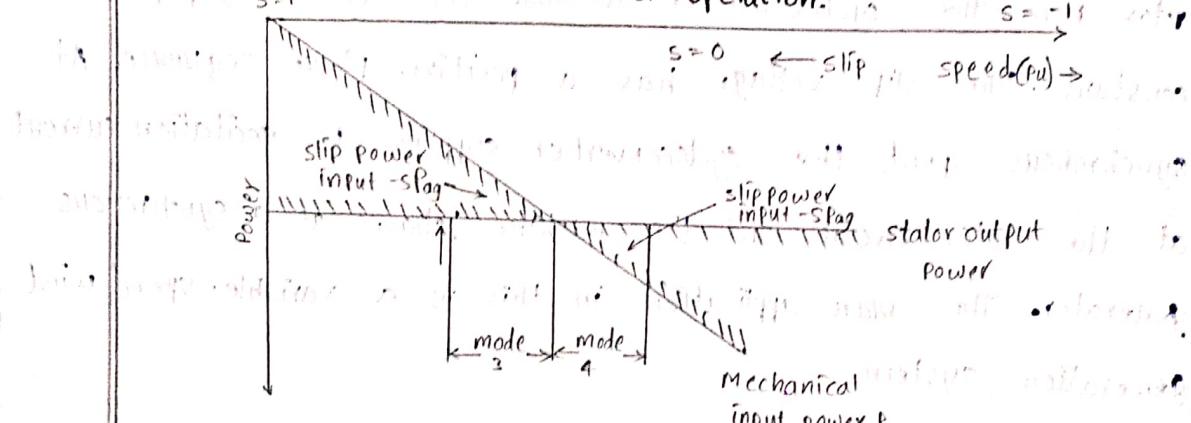


Figure 3.44(b): mode of operation

Advantages of static scherbius drive:

- 1) In this method, the problem of commutation near synchronous speed disappears.
- 2) The cycloconverter is to be controlled so that its output frequency tracks precisely with the slip frequency.

Disadvantages :

- 1) The cycloconverter cost is increases
- 2) The control of the scherbius drive is somewhat complex.

Applications :

- 1) multi-MW, variable-speed pumps/generators
- 2) flywheel energy storage systems

Problems :-

- i) The rotor of a 4-pole, 50Hz wound-rotor induction motor has a resistance of 0.3Ω per phase and runs at 1440 rpm at full load. calculate the external resistance per phase which must be added to lower the speed to 1320 rpm, the torque being the same as before.

Solution :-

Given data :-

$$P = 4, \quad f = 50\text{Hz}$$

$$R_2 = 0.3\Omega, \quad N_1 = 1440\text{rpm}$$

$$N_2 = 1320\text{rpm}$$

External resistance $R_e = ?$

$$\text{The motor torque } T = \frac{KSR_2}{R_2^2 + (sx_2)^2}$$

$$\text{since, } x_2 \text{ is not given, } T = \frac{KSR_2}{R_2^2} = \frac{ks}{R_2}$$

$$\text{In the first case, } T_1 = \frac{ks_1}{R_2}$$

$$\text{In the second case, } T_2 = \frac{ks_2}{R_2 + R_e}$$

where R_e is the external resistance per phase, added to the rotor circuit since $T_1 = T_2$

$$\therefore \frac{ks_1}{R_2} = \frac{ks_2}{R_2 + R_e} \Rightarrow \frac{s_1}{R_2} = \frac{s_2}{R_2 + R_e}$$

$$\text{Now } N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500\text{rpm}$$

$$N_1 = 1440\text{rpm}, \quad N_2 = 1320\text{rpm}$$

$$\therefore s_1 = \frac{N_s - N_1}{N_s} = \frac{1500 - 1440}{1500} = 0.04$$

$$s_2 = \frac{N_s - N_2}{N_s} = \frac{1500 - 1320}{1500} = 0.12$$

$$\frac{s_1}{R_2} = \frac{s_2}{R_2 + R_e} \Rightarrow \frac{0.04}{0.3} = \frac{0.12}{0.3 + R_e}$$

$$\boxed{\text{External resistance } R_e = 0.6\Omega}$$

2) If 40Ω is the resistance and 0.75 is the duty cycle for the induction motor speed control using chopper, what is the effective value of resistance R_e ?

Given data :-

$$R = 40\Omega$$

$$\alpha = 0.75$$

To find

$$R_e$$

solution :-

$$R_e = [R(1-\alpha)]$$

$$= [40(1-0.75)]$$

$$\boxed{R_e = 10\Omega}$$

3) Repeat problem in case there is an overloop angle of 120° in the rectifier and so in the inverter.

solution :-

Average output voltage for single phase full converter,

$$V_o = \frac{V_m}{\pi} [\cos \alpha + \cos(\alpha + 120^\circ)]$$

for uncontrolled bridge rectifier, dc output voltage is.

$$V_d = \frac{3\sqrt{2} S E_2}{2\pi} [\cos 0^\circ + \cos(0^\circ + 120^\circ)] = 2 \times 0.7$$

$$= \frac{3\sqrt{2} \times 0.2 \times 346.41}{2\pi} [1 + \cos 120^\circ] \div 1.4 = 158.8V$$

$$\text{Efficiency } \eta_v = \frac{P_{out}}{P_{in}} \times 100 = \frac{30000}{38177} \times 100$$

$$\boxed{\eta_v = 78.58\%}$$

d) Power factor

$$P_m = \sqrt{3} V_L I_L \cos \phi$$

$$38177 = \sqrt{3} \times 600 \times 151.13 \times \cos \phi$$

$$\boxed{\cos \phi = 0.243 \text{ (lag)}}$$